UNITED STATES DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

THE PHYSICAL BEHAVIOR AND GEOLOGIC CONTROL OF RADON IN MOUNTAIN STREAMS *

By

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*This report concerns work done on behalf of the Division of Research of the Atomic Energy Commission.

The report has not been edited or reviewed for conformity to Geological Survey standards and nomenclature.

May 1954

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ABSTRACT

Radon distribution ratio determinations in an air-water system were made. They checked very closely with those done by Kofler in 1913.

The distribution of radon in stream waters and related springs was investigated in the Wasatch Mountains adjacent to Salt Lake City, Utah, and in a part of the Weber River near Ogden, Utah.

The radon distribution in the stream waters studied forms a definite pattern which is dependent upon the local influx of relatively large amounts of radon-bearing ground water into the stream, and, in turn, the ability of the stream to lose its radon to the atmosphere through turbulance. The ability of the stream to lose its radon is governed largely by the gradient and rate of flow of the stream and the nature of the stream channel, and tends to reach an equilibrium value of less than one micro-micro Curie per liter. This loss of radon generally occurs as an exponential function with respect to distance of stream flow. The slope of the function varies with different streams.

The stream waters investigated contain from one (limit of the sensitivity of the instrument) to about 450 micro-micro Curies of radon per liter. The radon content of spring waters is generally higher than that of stream waters. The large radon contents mark the areas of ground water influx into the stream, although, in most cases, no spring activity

in these areas was observed. The high-radon anomalies can usually be related to definite stratigraphic horizons or structural features.

The amount of ground water being added to the stream can be estimated in some cases by radon measurements of stream waters and related springs.

Almost complete disequilibrium occurs between radon and its parent radium in stream and spring waters in this area.

The writer wishes to acknowledge the interest shown and suggestions made by Professors Kenneth L. Cook, Armand J. Eardly, and Lyle B. Horst of the University of Utah which have stimulated the progress of this research.

The Weber River investigations was done in cooperation with John H. Feth and Herbert A. Waite, of the U. S. Geological Survey, Ogden and Salt Lake City, Utah, respectively.

Thanks are also extended to the Salt Lake City Water Department for allowing access to the City Creek water shed, and to the Post Engineers of Fort Douglas, Utah for allowing access to the Military Reservation, which includes Red Butte Canyon.

The work described in this report was part of a program of investigations being carried on by the U. S. Geological Survey on behalf of the Atomic Energy Commission.

INTRODUCTION

General statement

Increased interest in uranium has stimulated progress in radiometric studies as related to geology. Radon, a radioactive gas, can be isolated and measured with relative ease, because of its unique characteristics.

This paper presents the results of an investigation of the possible uses of radon as a tracer in uranium exploration and ground-water problems. The paper is divided into two parts. Part I is concerned with the instrumentation and a recheck of previous determinations of radon distribution ratios in an air-water system. Part II describes (1) the distribution of radon in springs and streams draining a part of the central Wasatch Mountains adjacent to Salt Lake City, Utah, and (2) the results of an attempt to solve a ground-water problem concerning a part of the Weber River, near Ogden, Utah.

General considerations in radon analysis

Radon belongs to the family of inert noble gases and is the only naturally occurring radioactive gas.[X] As an element, radon is comprised of three isotopes,[XX] each of which disintegrates through alpha emission: Rn ^{222} (radon), with a half-life of 3.825 days; Rn ^{220} (thoron), with a half-life of 54.5 seconds; and Rn ^{219} (actinon), with a half-life of 3.92 seconds. These isotopes are members

[X] No, Th also occurs in nature. See Hunden's paper.

of the U ^{238}, Th ^{232}, and U ^{235}, families, respectively. Of the three isotopes, radon (Rn ^{222}) has the most convenient half-life for measurement, and is the only isotope investigated in this report.

The interrelation of half-lives of the parent radium and the immediate daughters of radon adds to the convenience of radon measurements. The half-life of radium (Ra ^{226}) is 1,620 years, and may be considered infinite compared to the 3.825-day half-life of radon. Approximately 99 percent equilibrium is established between radon and radium within 25 days. (Geiger, 1943, p. 278 1/). The hourly growth and decay of radon up to twelve days is given by Jennings and Russ (1948, p. 212-213).

Radon disintegrates through a series of four short-lived daughter products, with which equilibrium is established in about four hours. (Jennings and Russ, 1948, p. 42, and p. 210-211).

Pb ^{210} (RaD), the next (i.e. fifth) daughter product after radon, has a half-life of 22 years, which, compared to four hours, is sufficiently long that the effect of Pb ^{210} in radon measurements is negligible.

The unit of measurement most commonly used in radon determinations is the Curie, but because the Curie is a very large unit, the milli-micro Curie or micro-micro

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1/ This table shows the decay of radon; however $1-e^{-\lambda t}$ may be used for the buildup of equilibrium.

Curie is conventionally used. The Curie is defined as the amount of radon in equilibrium with one gram of radium. It has been further defined as 3.70×10^{10} radioactive disintegrations per second. A Curie, in terms of radon volume at standard temperature and pressure, is 0.66 mm^3. Thus, 0.66×10^{-12} mm^3 of radon gas, which is equivalent to one micro-micro Curie, and is measurable, gives an indication of the minute quantities of radon which can be quantitatively measured. Other units which have been used are the Mache unit, which is equal to 3.6×10^{-10} Curie per liter, and the Eman unit, which is equal to 1×10^{-10} Curie per liter. (Hevesy and Paneth, 1926 p. 178).

Radon can be measured by the ionization effect produced by alpha emission in an ionization chamber. The degree of ionization is a measure of the radon present in the chamber. It is measured by the rate of fall of a charged gold leaf of an electroscope, or by a suitable device capable of counting individual pulses, or by measuring the total ionization current produced by the alpha emission.

Of all the radioactive isotopes of the U^{238} family, radon, being an inert gas, is most susceptible to migration. Migration is accomplished by either gaseous diffusion or solution. In gases and waters, radon is commonly found almost completely out of equilibrium with its parent, radium. The ability of radon to migrate away from its source suggests that it may be useful as a tracer isotope in uranium exploration. The distance of migration is

dependent upon the 3.825-day half-life, the rate and medium of migration and possibly other factors such as adsorption of radon on carbonaceous material.

Since all rocks contain uranium to some extent, radon may prove to be a useful tracer in some ground-water problems.

Purpose and scope

The purpose of the present investigation is to determine some of the relationships between geologic conditions and radon concentrations in waters, and extend the usefulness of radon as a geologic tool. During the present investigation, marked differences in radon content were discovered in the water of streams and related springs. These differences are correlated with natural conditions, both geologic and non-geologic.

Although radon distribution ratios between air and water are important in correlating radon contents of liquids with large temperature or solid content differences, these ratios were not used in the interpretation of radon contents in stream waters. In some methods of radon analysis, the liquid sample is taken directly into an ionization chamber, and the air-water distribution ratio must be accurately known. The ratios, as determined by previous workers, were checked in part, because of recent advances in instrumentation and the availability of more efficient high resistance insulation materials.

Previous work

Radon has been variously called "radium-emanation" and "niton" by early investigators. The basic physical properties of radon are given by Rutherford (1913), Geiger (1943), Jennings and Russ (1948), and Wahl and Bonner (1951). These texts also contain data and additional references on distribution ratios which are also called "partition ratios" and "solubility coefficients".

An abundance of literature on the radioactivity of spring localities is available. Perhaps the most intensive and complete studies in this country are currently being conducted by Kuroda and his co-workers in Hot Springs National Park and vicinity, in Arkansas, where radon concentrations, in both hot and cold springs, and in streams, are related to geologic features and known uranium-radium mineralization (Arndt and Kuroda, 1953) (Kuroda, Damon, and Hyde, 1954). The work of Arndt and Kuroda (1953) probably represents the first published correlation of radon occurrences in stream waters with geology.

Miholić (1952) analyzed water from 26 springs in Yugoslavia and found that the waters from Carboniferous and Cretaceous strata contain more radon than the waters from sedimentary rocks of other periods.

At Yellowstone National Park, radon determinations of gases and waters, and radium determinations of spring deposits, were made by Schlundt and Moore (1909).

The U.S. Geological Survey recently completed a detailed investigation of radon and helium in the West Panhandle Gas Field of Texas, the Hugoton gas field of Kansas, and other gas fields in the Mid-Continent region. Although the results have not as yet been published, a preliminary report is available (Faul, et al., 1953).

Kovach (1944, 1945, 1946) describes, in a series of papers, a method of determining radon in soil gas. He describes his technique fully and notes variations in radon content that are attributable to depth of sampling, and meteorological effects, such as snow cover, barometric pressure, and wind velocity. A similar study by Norinder, Metnieks, and Siksna (1953) was made at Uppsala, Sweden.

The general subject of radioactivity and nuclear physics, as applied to geology, is very well treated in a symposium volume which is now in press (Faul, 1954). Included in this volume are sections pertaining to theory, methods of analysis, and natural occurrences of radon. Picciotto (1951) also gives a brief summary of radioactivity, as applied to geology.

PART I

INSTRUMENTATION AND EQUIPMENT

Theory

A product of radioactive disintegration, such as an alpha particle, beta particle (electron), or gamma-ray (photon), produces ionization in the medium through which it passes. The number of ionizing events, which are initiated by individual radioactive disintegrations, can be detected and measured by means of an ionization chamber.

An ionization chamber generally consists of a gas-filled cylindrical cathode and an axial anode. When a voltage is applied across the cathode and anode, the ions induced by each ionizing event will drift and produce an electrical pulse. The type of radiation which can be detected and counted is dependent upon the voltage impressed across the chamber. The chamber acts as an alpha counter in the low-voltage range of about 50 volts. By progressively increasing the voltage, the chamber functions as a proportional counter and then as a geiger counter at a voltage of 800 to 1,000 volts.

The electrical pulses produced by each ionizing event can be measured as individuals or they can be accumulated and integrated as a total current.

The theory of counters is given by Korff (1946) and Halliday (1950).

For the measurements given in this paper, an ionization

chamber was used as an alpha counter, with an attached Vibrating Reed Electrometer to measure total ionization current.

The Vibrating Reed Electrometer

The Vibrating Reed Electrometer (Palevsky, Swank, and Grenchik, 1947) is a current-measuring instrument capable of detecting currents in the range produced by ionization chambers (1×10^{-12} to 1×10^{-17} amperes [1]). These small direct currents are impressed upon a condenser, one plate of which vibrates at a frequency of 450 cycles per second. Thus the direct current is converted to a cyclic current, which can be amplified and measured. A graphic recorder attached for a permanent, continuous record of the measurements, was used in the present work.

Principles of method employed

Radon can be measured quantitatively in a gas or a liquid. A gas sample is introduced directly into an evacuated ionization chamber. In liquids, radon is boiled out of the sample into an evacuated ionization chamber, while argon is simultaneously bubbled through the boiling liquid sample in order to carry the radon from the sample

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[1] Instruction Manual for Vibrating Reed Electrometer, Model 30: ~~Allied~~ Applied Physics Corporation, Pasadena, California.

into the chamber. After the radon has been isolated in the chamber for a 4-hour period, during which time the radon has established equilibrium with its short-lived daughter products, the ionization current produced by alpha emission is measured by the Vibrating Reed Electrometer. A continuous record of the amplified current is recorded on a one-milliampere graphic strip-chart recorder.

The current measurements of the unknown samples are compared directly with the current produced by a known amount of radon evolved from a standard radium solution obtained from the National Bureau of Standards, Washington, D.C. The 10.5×10^{-12} gm standard radium solution is measured periodically. The average of 20 such measurements, which vary ± 4 percent, gives a conversion factor, in terms of micro-micro Curies per milliampere, which is used in all the unknown determinations.

Background measurements using "dead" argon are also determined periodically, and subtracted from all measurements. The lower limit of radon measurement by the method discussed here is about one micro-micro Curie per liter.

Radium contents of liquids are determined in a similiar fashion, except that two boilings of the liquid sample are necessary. First, all radon is driven from the sample either by making a radon determination, or by boiling it to the atmosphere, thus establishing a "zero" point. Several days after the "zero" point has been established, the radon which evolved from the radium in

the sample is driven into an ionization chamber, and measured. The amount of radon evolved gives a measure of the amount of the radium in the sample.

Time is an important factor in both radon and radium determinations. The radon content of each sample is referred to the time of sampling. Thus the amount of radon which decayed during the time between sampling and determination must be accounted for. Because of its 3.825-day half-life, radon determinations are generally made within three days after sampling.

The time between sampling and measurement in radium determinations is not critical, but the time of radon evolution or build-up must be accurately known. The state of radon-radium equilibrium is used as a reference point, and all radium measurements are corrected to this point. As radon builds up to 50 percent in 3.825 days, a build-up time of four days is usually sufficient, except in cases of low radium concentrations.

Equipment

The equipment and experimental setup used throughout the present investigation are fashioned after two similiar arrangements constructed by Henry Faul and John Rosholt of the U.S. Geological Survey, Denver, Colorado. The most significant change from Faul's and Rosholt's apparatus is the writer's use of tygon tubing in the gas transfer system. The photos (Plate 1), and diagrammatic sketch (Plate 2)

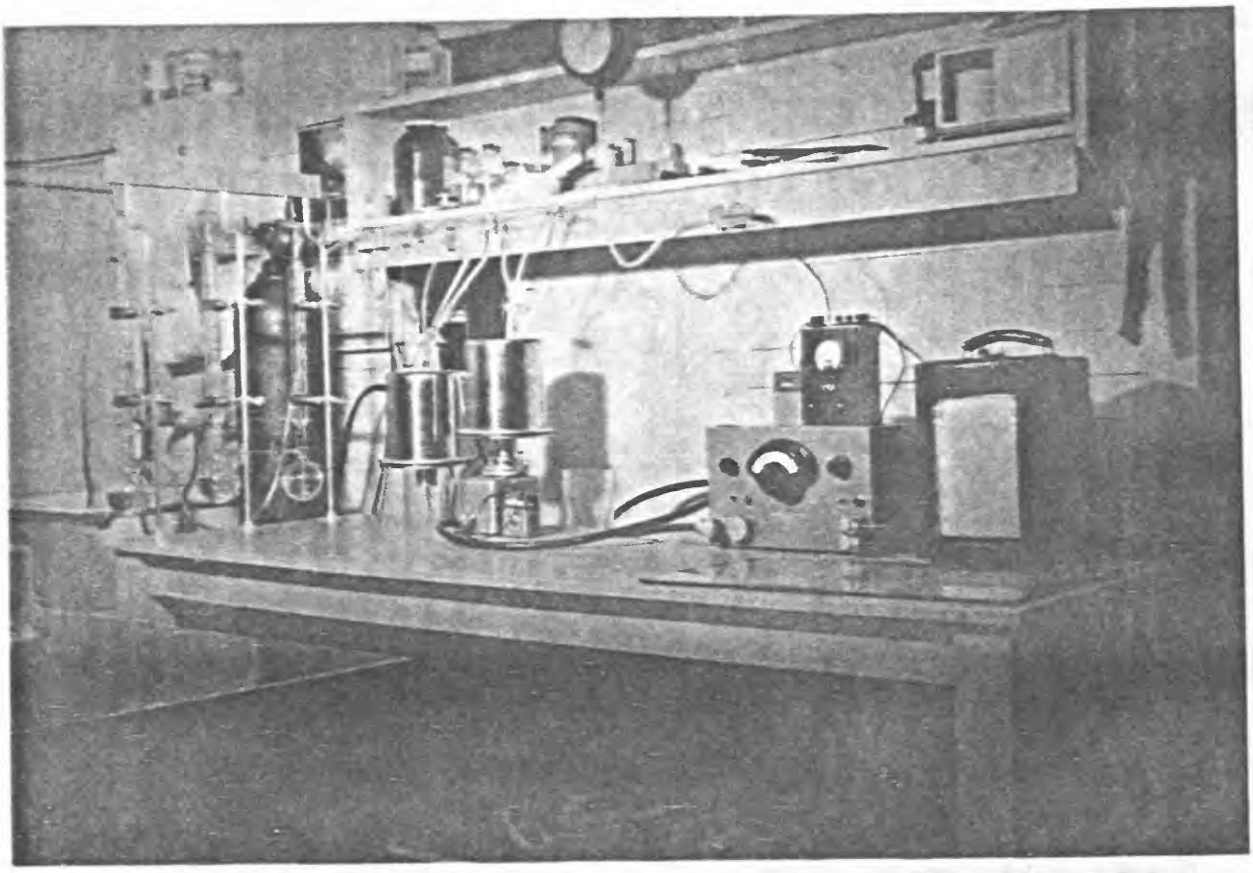
show the writer's equipment arrangement. The component parts are listed on Plate 2.

The equipment consists of a bank of three 500-milliliter reflux boilers and two 4.2-liter-capacity stainless steel ionization chambers with a connecting gas transfer system (Plates 1 and 2). The gas transfer system consists of two parts: the intake line from the boilers with attached U-tube desiccator and vacuum gauge, and the exhaust line with its vacuum pump and vacuum thermocouple tube. The ionization chambers are connected to both lines. The two lines are connected by a "bridge" stopcock. When the "bridge" is closed, it is possible to fill one chamber while evacuating the other.

All water samples are collected in gas sampling tubes of approximately 300 ml volume (Plate 4). The tubes are filled by applying suction to one end of the tube. When full, the sample is transferred directly to the reflux boiler, through the argon intake, by partial vacuum.

Tygon tubing system

The gas transfer system is made entirely of tygon tubing (3/8 inch x 1/4 inch) with glass joints and stop-cocks. Tygon tubing has certain advantages over the conventional all-glass or copper tubing systems. It is cheap, and easy to construct and maintain. Changes in the system can be made easily. The cleaning of a contaminated glass or copper tubing system can be a tedious



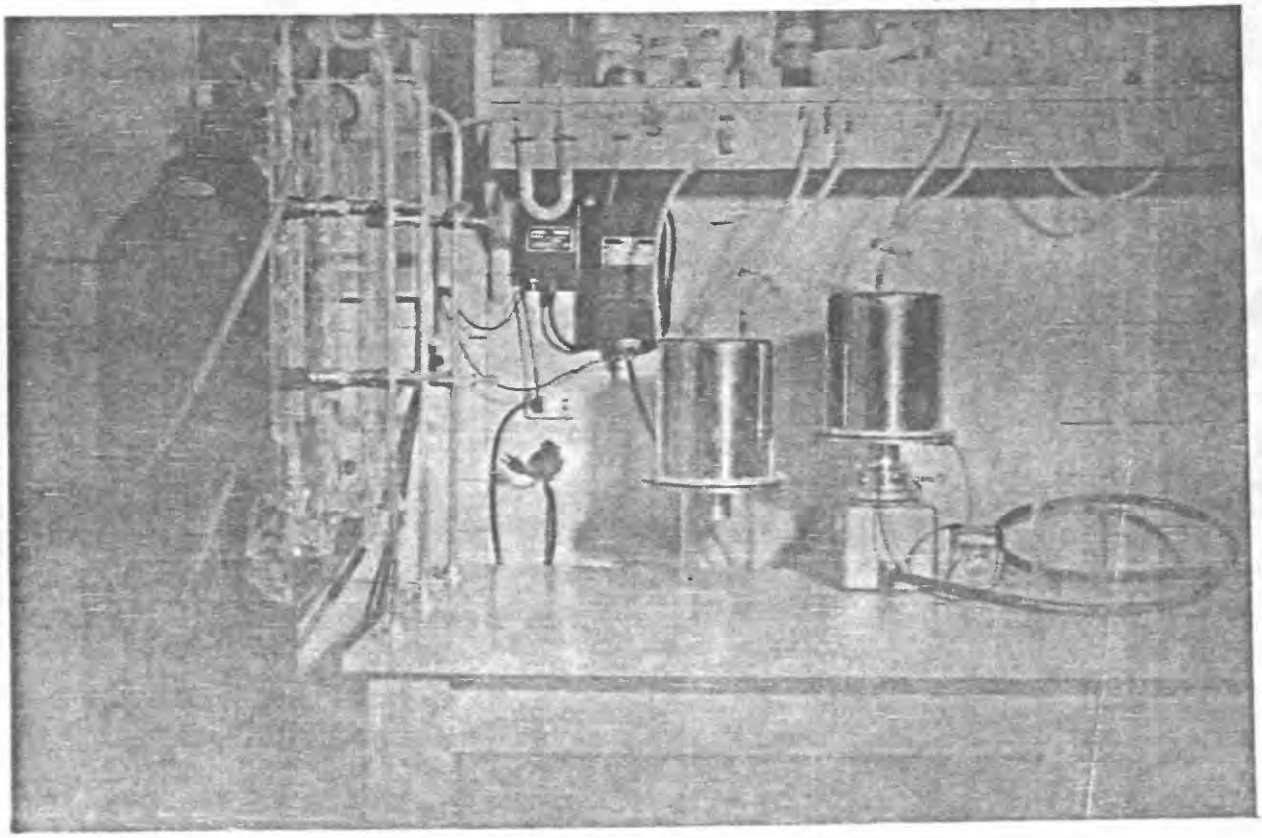
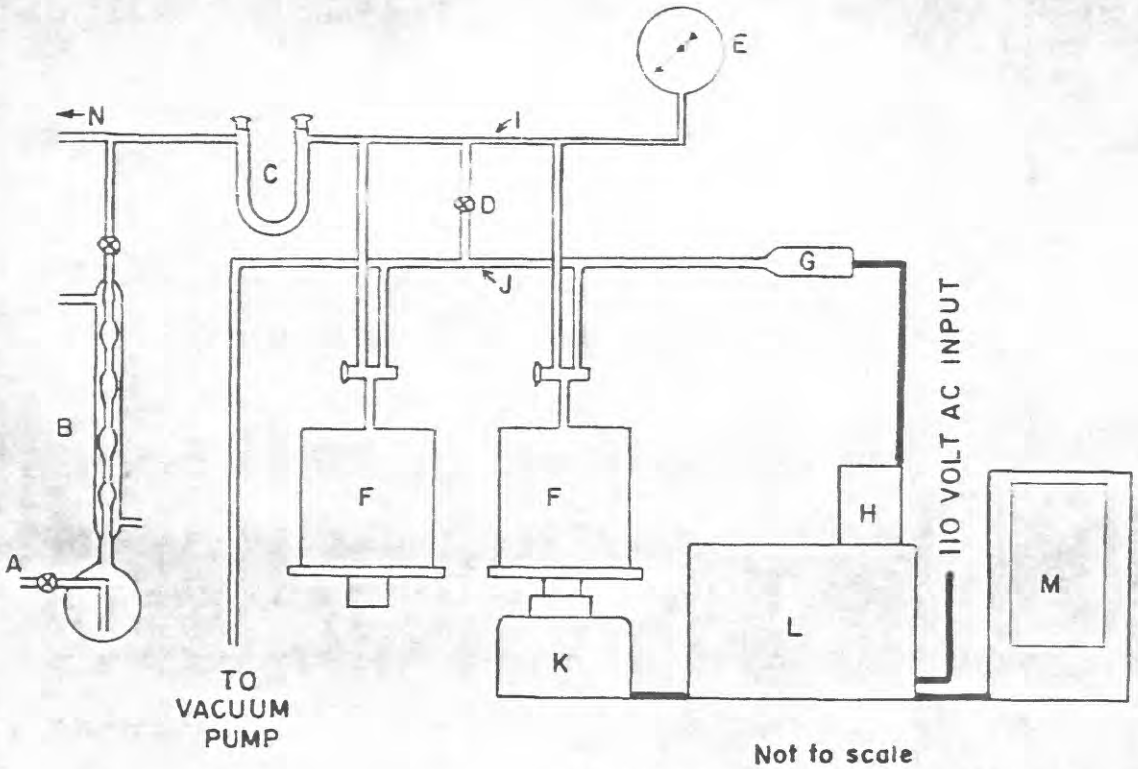


Plate 1 - Radon measuring apparatus.



Not to scale

Electrical connections — solid black

A – ARGON AND SAMPLE INTAKE
B – 500 ml REFLUX BOILER
C – U TUBE DESICCATOR
D – "BRIDGE" STOPCOCK
E – VACUUM GAUGE
F – IONIZATION CHAMBERS
G – VACUUM THERMOCOUPLE TUBE
H – VACUUM THERMOCOUPLE CONTROL UNIT
I – INTAKE LINE
J – EXHAUST LINE
K – VIBRATING REED ELECTROMETER
L – VIBRATING REED ELECTROMETER AMPLIFIER
M – ONE MILLIAMPERE STRIP-CHART RECORDER
N – TO TWO ADDITIONAL REFLUX BOILERS

Plate 2 - Diagrammatic sketch of apparatus.

job; but if the tygon tubing becomes contaminated, it may be discarded and replaced by new tubing. A tygon system is not susceptible to the breakage of a glass system. Although the equipment was originally set up as a semi-permanent installation in a laboratory, the tygon system was constructed with the idea that the equipment will eventually be installed as a mobile truck-mounted unit.

The vacuum characteristics of the tygon system are sufficient for radon determinations. The entire system, together with the two chambers, can be evacuated to about 150 microns of mercury. After a period of ten minutes, without pumping, the vacuum decreases to about 600 microns of mercury.

None of the tygon tubing-glass connections developed leaks during one year of almost daily use. A low vapor pressure silicone grease is used as a seal and lubricant in the connections. No organic greases or black rubber should be used because they tend to adsorb radon.

A few limited experiments by the writer showed that no appreciable radon is lost in the tygon system by adsorption or diffusion. Radon was allowed to expand freely from a full ionization chamber through about 20 feet of tygon tubing into an evacuated chamber. The radon was then measured in each chamber and generally showed less than one percent difference. R.D. Evans (1953) investigated radon losses in black rubber, gum rubber, and tygon tubing. His results indicate that the loss

of radon to gum rubber or tygon tubing is negligible if the volume of the radon-air (radon-argon in the writer's case) at any time is small compared to the total volume collected.

RADON DISTRIBUTION RATIOS

General statement

The distribution ratios of radon between various gases and liquids has been measured by many investigators. When radon with equal volumes of liquid and gas is shaken in a closed container, the radon is distributed to each phase in amounts dependent primarily upon temperature and the nature of the liquid. The radon content of each phase is measured, and the ratio Rn liquid / Rn gas is the "distribution ratio", which is also called "solubility coefficient" and "partition ratio".

In view of the recent advances in radiometric instrumentation and insulating material, the distribution-ratio determinations of previous investigators were checked. Although the ratios are not used in Part II of this paper, they may be important in the correlation of radon contents of gases and liquids where different liquids and large temperature changes are involved. In some methods of radon analyses in which the water sample is taken directly into an ionization chamber, the distribution ratios must be accurately known.

Previous work

The works of Rutherford (1913), Geiger (1943), Jennings and Russ (1948), and Wahl and Bonner (1951) contain data and numerous references on the distribution ratios of radon.

Kofler (1913) investigated the distribution ratios in various air-liquid systems. The liquids include water, and aqueous sodium chloride, barium nitrate, ammonium nitrate and urea solutions.

The results of the present investigation are compared to those of Boyle (1911), Kofler (1913), and Hevesy and Paneth (1926).

Method

The method described here, and those of previous investigators, are essentially the same, although the closed containers used for radon partition and the methods for determining radon in the gas and liquid phases are different.

The radon partition device used in this investigation consists of a 500 ml glass globe with three stopcocks and a thermometer well (Plate 3).

The following is a description of the method used here to determine radon distribution ratios at various temperatures. The gases used were nitrogen, air, and a commercial natural gas. Distilled water was used as the liquid phase.

The partition device is flushed with nitrogen - or some other gas, depending upon the system being investigated - and filled half full with water. The nitrogen above the water is evacuated which causes the water to boil. This is of no importance, although it does remove all extraneous gases from the liquid phase.

Nitrogen is bubbled through an 8×10^{-9} gm radium solution and taken into the evacuated volume above the liquid phase until a pressure of one atmosphere is attained. Approximately 60 percent of the total radon built up by the radium solution is driven into the partition device by this method. The amount of radon, which remains in the radium solution and connecting lines, is also measured; and its measurement serves as a check.

At this point the partition device contains equal volumes of water and nitrogen-radon mixture.

A thermometer is set in the thermometer well, with mercury around the bulb for good conduction, and the device is placed in a constant temperature bath. After a constant temperature has been established, the partition device is shaken vigorously for two minutes in order to distribute the radon to the gas and liquid phases. Equilibrium of radon distribution to the two phases occurs after about 15 to 20 seconds.

At temperatures divergent from room temperature, the device is shaken periodically through a time interval

of several hours. When the temperature starts to rise or fall, the partition device is replaced in the constant temperature bath.

The two phases are separated, and their radon contents are determined. Connection "C" of the partition device (Plate 3) is joined to the argon intake of a partially evacuated reflux boiler. A nitrogen pressure of several pounds is maintained in the partition device while the water phase is transferred to the boiler. The separation takes about 10 seconds, with a loss of a few drops of the liquid phase and perhaps a milliliter of the gas phase. The radon from both phases is introduced into the gas transfer system at the same point in order to reduce any variations due to the geometry of the system. Both phases are separately measured for radon content. The ratio, Rn in water / Rn in gas, is the distribution ratio.

Although all distribution-ratio determinations were made at a constant pressure of one atmosphere, this is not critical. Boyle (1911) reports no change in distribution ratios at constant temperature in a pressure range of 9.0 cm to 183 cm mercury.

Results

The results are shown on Figure 1. The graph is a plot of the radon distribution ratios at various temperatures. The results from Boyle (1911), Kofler (1913),

and Hevesy and Paneth (1926) are included on the same graph.

Nitrogen, air, or natural gas can be used as the gas phase with no apparent effect on the distribution ratio of radon. The ratios are also independent of radon content. Nitrogen was used for most measurements in the present investigation. The present results of distribution ratios agree very well with those of previous workers.

Distribution ratios in other liquids

Gases are generally less soluable in aqueous solutions of electrolytes than in pure water. This phenomenon is known as the salting-out effect (Glasstone 1946, p. 699). The salting-out effect of an ion varies inversely with its size, and directly with the charge it carries.

Kofler (1913) has investigated the distribution ratios of radon in various salt solutions. His results on sodium chloride solutions of various concentrations (S = specific weight and α = distribution ratio) are shown in Figure 2.

Radon is very soluable in organic liquids. The distribution ratio can be as large as 23 in some liquids. (Wahl and Bonner, 1951, p. 157).

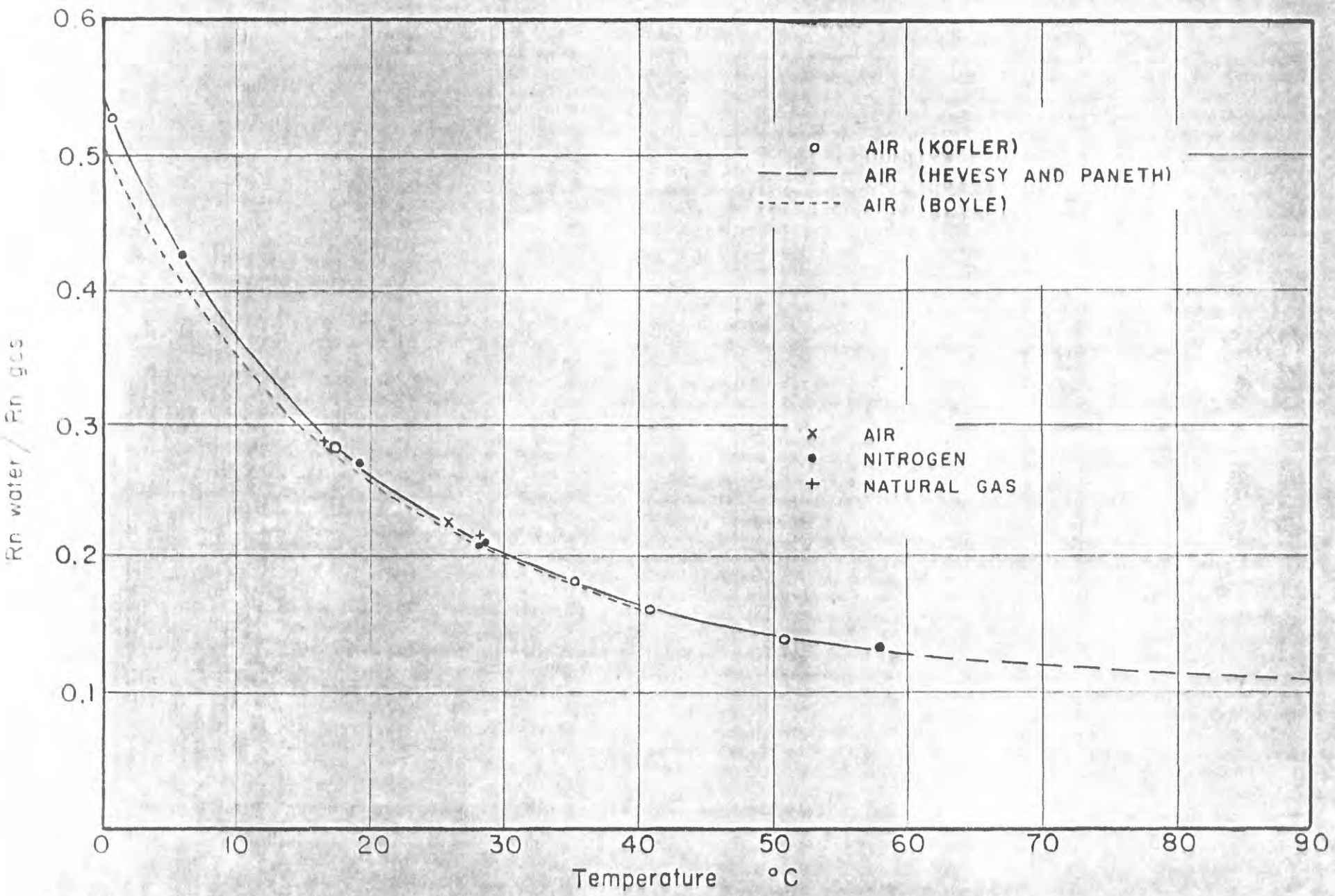


Figure 1 - Radon distribution ratios in an air-water system.

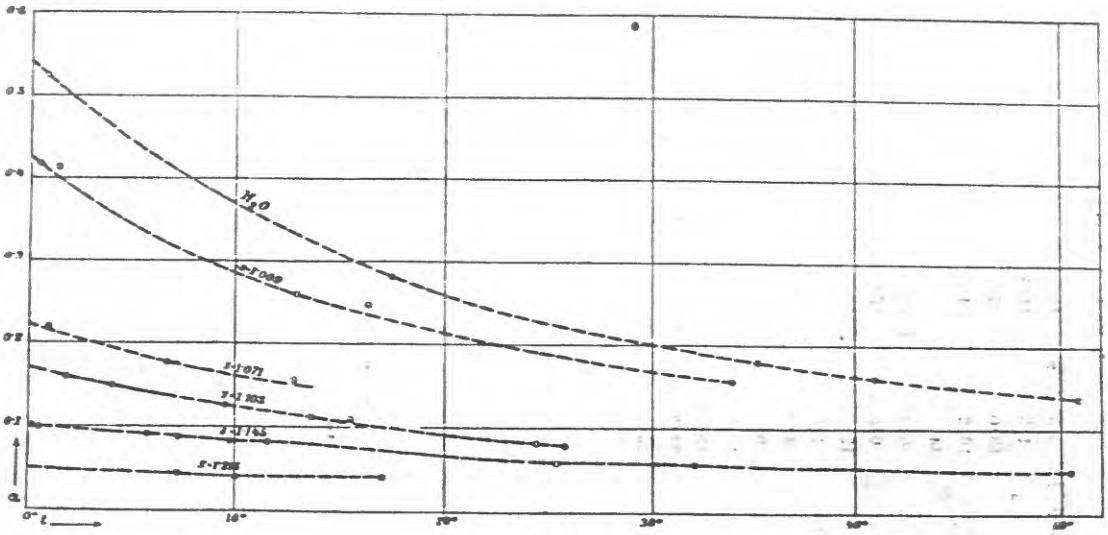


Fig. 1.

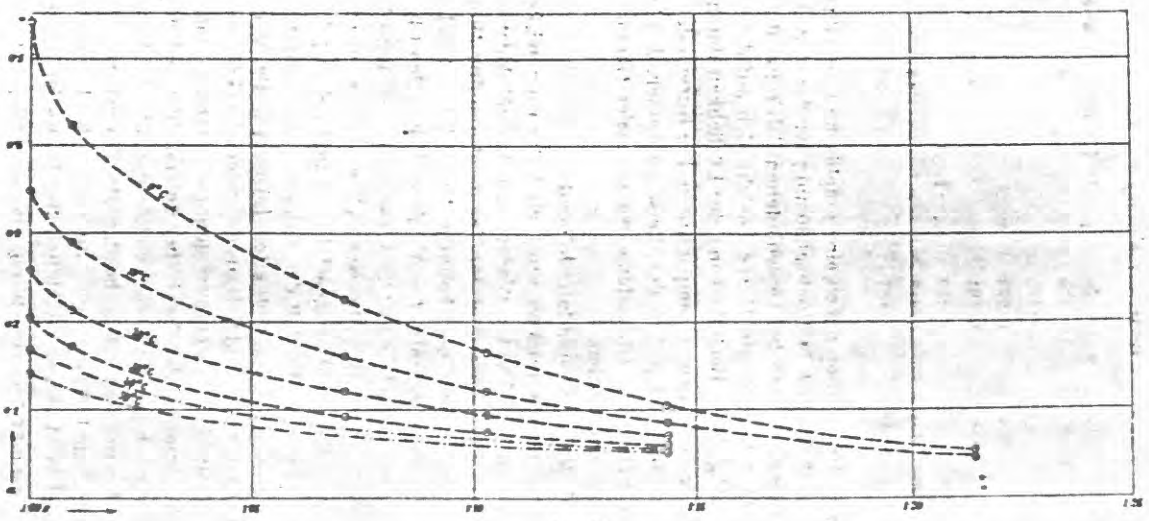


Fig. 2.

Figure 2 - Radon distribution ratios in an air-sodium chloride solution system.

PART II

RADON DISTRIBUTION IN SURFACE WATERS DRAINING PARTS OF THE WASATCH MOUNTAINS

General statement and previous work

Radon, an inert gas, has the ability to migrate away from its parent radium, by gaseous diffusion or solution. This ability to migrate provides possibilities for its use as a tracer in uranium exploration. Perhaps more important are the potential applications of radon determinations to the solution of ground-water problems, particularly those which involve bedrock aquifers.

Very little is known concerning the correlation of radon in stream waters to geologic conditions. Arndt and Kuroda (1953) conducted a reconnaissance survey of radon contents in streams and lakes in parts of Garland and Hot Springs Counties, Arkansas. A correlation between radon in streams and the rock types over which the streams flow was suggested where the rock types crop out over wide areas. The radon content of streams and springs proved higher near known uranium mineralization, and the applicability of radon determinations in the field to prospecting for low-grade uraniferous deposits was discussed. Arndt and Kuroda (1953) also proposed that the radon content in streams was a reflection of ground-water influx into the stream.

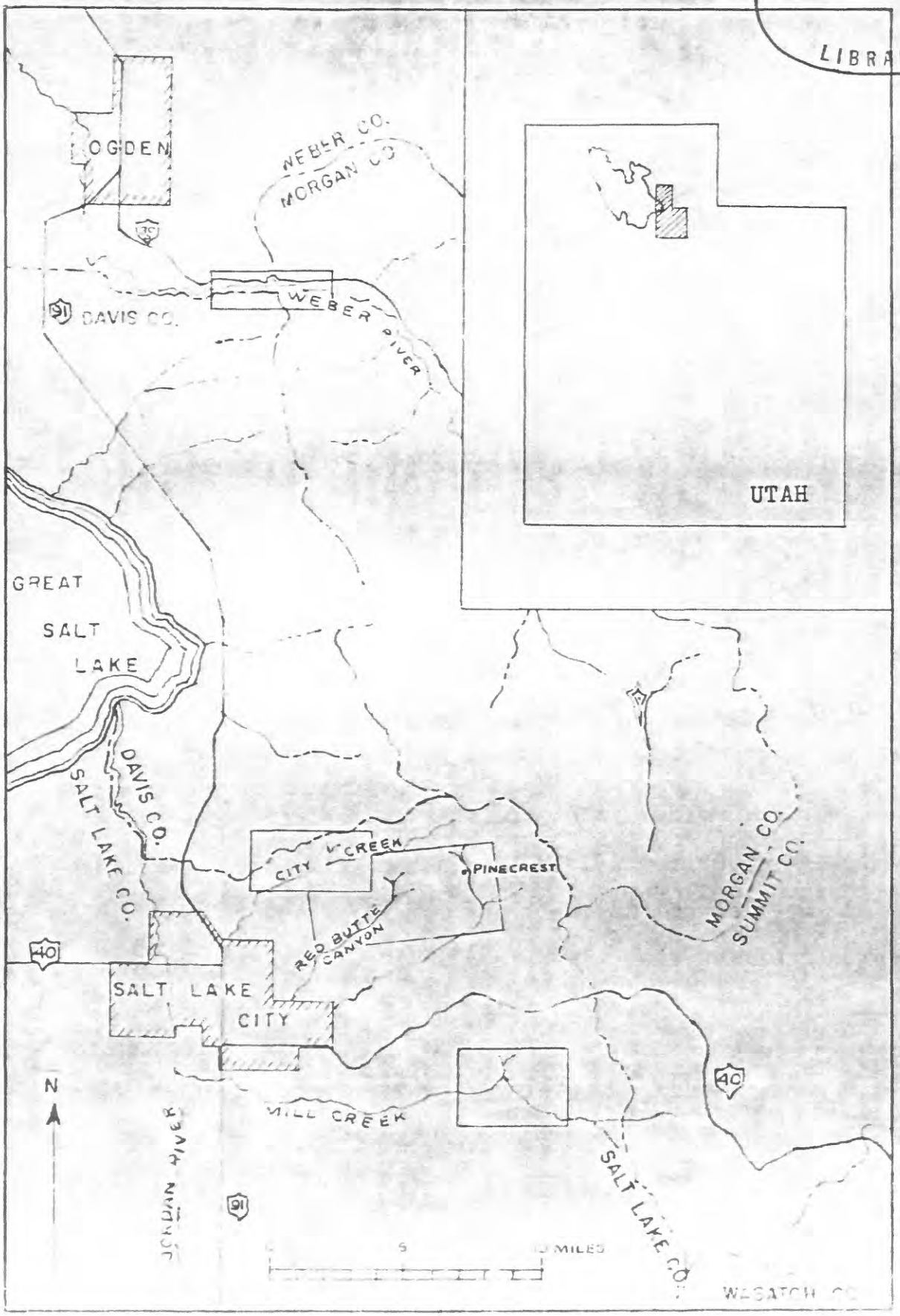


Figure 3 - Index map showing location of radon surveys

The present investigation concerns the distribution of radon in stream waters and related springs, and the relation of the distribution to both geologic and non-geologic conditions, in several drainage areas of the Wasatch Mountains adjacent to Salt Lake City, Utah.

A similar investigation was correlated with ground - and surface - water studies in a part of the lower Weber River drainage area near Ogden, Utah.

Description of the area

The Wasatch Mountains extend from Nephi, in central Utah, northward into Idaho. Their western face forms part of the eastern limit of the Basin and Range province. Salt Lake City is situated in the northeast margin of Jordan Valley near the steep front of the central Wasatch Mountains.

The area adjacent to Salt Lake City, which includes Red Butte Canyon, City Creek, and Mill Creek has a relief of 2,500 to 5,000 feet above the floor of the valley. In general the high points in the area are near the west edge of the range overlooking the valley.

General geology

In the area adjacent to Salt Lake City, the major structural element of the Wasatch Mountains is a broad eastward-trending syncline, which is modified by smaller

folds along its trough. The sedimentary rocks range in age from pre-Cambrian to early Tertiary. The syncline is flanked on the south by the Cottonwood uplift and on the north by the northern Utah uplift. The formation of the uplifts and the eastward-trending folds occurred during the early Laramide orogeny. Broad gentle northward-trending folds with about 5,000 feet of relief, and associated longitudinal faults were superposed on the pre-existing eastward-trending structures during middle or late Eocene time. The central Wasatch was probably represented by one of the anticlines. (Eardley, 1951).

Periodic episodes of gentle folding, uplift, and high-angle faulting continued through Tertiary time, with rejuvenation through Pleistocene and Recent times accompanied by high-angle faulting along the western border of the Wasatch Range (Marsell, 1953). A more complete discussion of the geology of the Wasatch Mountains near Salt Lake City, Utah, is given by: Eardley (1951), Granger and Sharp (1952), Marsell (1953), and Granger (1953).

The formations and structures are described briefly in the sections on the individual radon surveys.

Sampling technique

All samples were usually taken from the center of the stream at a depth of about one inch, and were confined primarily to fast-flowing parts of the streams. All stagnant pools and beaver ponds were avoided.

All samples were collected in gas sampling tubes of approximately 300 ml volume. (see Plate 4). The tubes, after having been flushed with argon, were filled by suction and the sample was then isolated. Once isolated, the water samples were introduced directly into a reflux boiler with no exposure to the atmosphere.

Radon is rapidly flushed from any water sample that is allowed to mix with the atmosphere. By collecting a water sample in a bottle and measuring out a volume in a graduate and then pouring the measured volume into a reflux boiler, it was found that about 45 percent of the radon is dissipated to the atmosphere. Kuroda, Damon, and Hyde (1954) report the same phenomena.

Radon surveys in streams

In the spring of 1953 a few preliminary radon determinations were made in several streams which drain the Wasatch Mountains near Salt Lake City, Utah. These samples showed sufficient range in radon content to warrent further investigation. The investigation was postponed until the summer of 1953, when the streams reached a stable condition and were not effected by snow melt. At that time another series of preliminary radon measurements, taken periodically over an interval of one week, at several localities, generally showed little variation in the radon content found at each locality. Therefore it seemed reasonable to assume that significant interpretations were possible concerning the

distribution of radon in stream waters.

A radon survey of stream waters and related springs was then made in the Red Butte Canyon and Pinecrest area, and parts of Mill Creek and City Creek (see Index Map - Figure 3, and Plates 5, 6 and 7). During the major part of these surveys (about two months) the rainfall in Salt Lake City was 0.19 inches. Presumably the rainfall was somewhat higher in the mountainous areas under investigation, but not in sufficient quantity to effect the stability of the streams.

Red Butte Canyon and Pinecrest area

Plate 5 shows the geology of the Red Butte Canyon and Pinecrest area, as taken from Granger and Sharp (1952), and the distribution of radon in streams and related springs.

The sedimentary rocks in the area range in age from Pennsylvanian to Tertiary. The oldest formation is the Weber quartzite of Pennsylvanian age with an estimated thickness of 1,200 feet. Apparently conformably overlying the Weber quartzite is the Park City formation, of Permian age. Granger (1953) measured a thickness of 974 feet of Park City formation at the head of Red Butte Canyon. For the most part, the Park City formation is made up of limestone with a thick, somewhat phosphatic, shale member in the middle of the formation.

Approximately 3,600 feet of Triassic sediments overlie the Park City formation, and include the Woodside red shale,

the Thaynes marine limestone and shale and the Ankareh red shale, siltstone, and sandstone. The Thaynes formation, which is of particular interest in the present investigation, has a thickness of 1,931 feet (Granger, 1953) and consists primarily of shales, sandy and shaly limestones, and one or more beds of gray limestone, which form prominent ridges.

The Triassic sediments are overlain by approximately 4,700 feet of Jurassic sandstones, argillaceous limestones, and red siltstones.

The Kelvin conglomerate and red siltstone of Cretaceous age, overlies the Jurassic strata with apparent conformity and is about 1,500 feet thick.

Unconformably overlapping the older rocks in the northern part of the area is the Almy conglomerate, of Tertiary age.

The streams in the Red Butte Canyon and Pinecrest area are small, with steep gradients. The flow at Points A, C, and E (see Plate 5) is probably about one cubic foot per second. The average stream gradients are: B to A - about 300 feet per mile, D to C, and including the headwaters - about 850 feet per mile, and from either F or G to Pinecrest - about 800 feet per mile.

The radon content of stream waters and springs (marked with an asterisk) is shown on the map in micro-micro Curies per liter. All repeat samples at the same localities are in brackets.

At the outset of the first radon survey in the Red Butte Canyon and Pinecrest area, stream samples were taken at widely spaced intervals, usually near prominent outcrops and changes in lithology. When a large amount of radon was found in the stream, samples were taken both upstream and downstream from the point of the anomaly. It soon became evident that the source of the radon could be established with respect to the stream, and that short sample intervals were necessary.

The distribution of radon in the stream waters forms a rather definite pattern. The springs, at the sources of the tributaries, contain relatively high radon contents. As the water moves down stream, the radon content decreases rapidly, in some places almost completely within 500 feet. Farther downstream, large anomalies of radon content are noted in stream waters and the radon content again rapidly decreases downstream.

The pattern of radon distribution in stream waters is apparently dependent upon the influx of radon-bearing ground water into the stream, and, in turn, upon the ability of the stream water to lose its radon to the atmosphere.

Since air usually contains less than one micro-micro Curie per liter, the radon in the stream water is out of equilibrium with that in the atmosphere and therefore tends to decrease and approach equilibrium (see Figure 1, concerning the distribution ratios of radon). After a large amount of radon has been introduced into the stream

by ground water, it is quickly released and flushed into the atmosphere. The rate at which this takes place is governed by the volume and gradient of the stream, and the nature of the stream channel. Several plots of radon content versus distance of stream flow downstream shows that the loss of radon to the atmosphere occurs as an exponential function with somewhat varying slopes in different drainage areas (see Figure 4).

The radon anomalies mark areas where large amounts of ground water relative to the stream volume is being added to the stream, although generally no evidence of spring activity is apparent.

A ground-water source for the anomalous radon concentrations in stream waters is postulated for the following reasons:

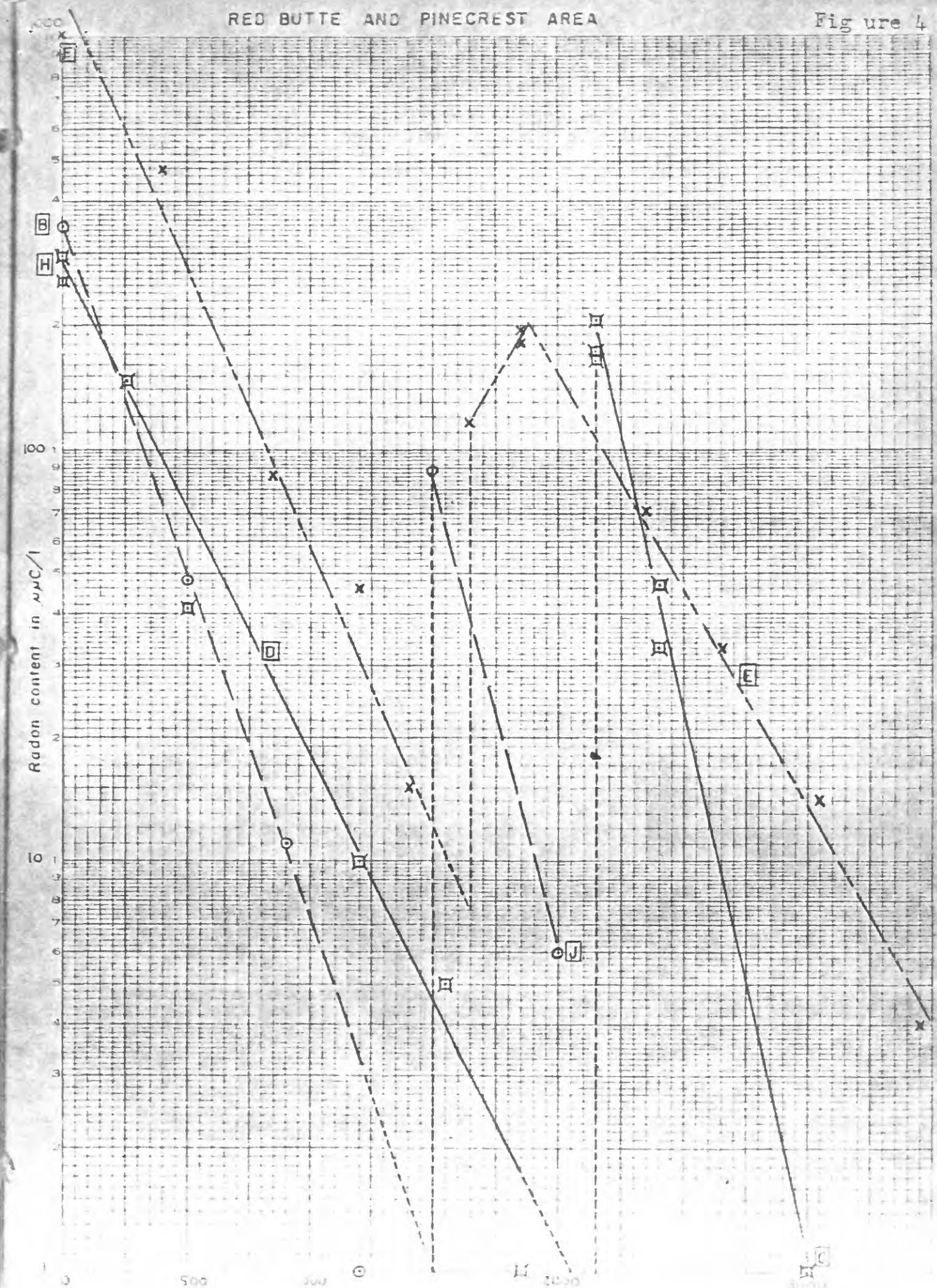
1. The springs in the area generally contain more radon than the stream waters and seem to be the only logical source.

2. The decay constant for radon is 0.007551 per hour or 0.000126 per minute. This shows the fraction of radon per unit time that will build up from a radium source. Hence, it seems unlikely that the radium content of the rocks in the stream channel will contribute much radon to the stream waters, because the radon will be continuously and swiftly swept downstream and dissipated to the atmosphere.

3. Surveys with a scintillation counter showed no abnormally high radioactivity in the rocks along the stream

RED BUTTE AND PINECREST AREA

Figure 4



channels. On the contrary, the limestones in the area, with which most radon anomalies in the stream waters are related, show a normal, lower, background reading than that of the adjacent shales.

4. A more definite relation of high radon contents in streams to related radon-bearing springs is shown in the Mill Creek area and the Weber River area.

The areas of relatively large amounts of ground-water influx, or aquifers, thus marked by radon anomalies, can be related to rather definite stratigraphic horizons. The anomaly in the Thaynes formation in the Pinecrest area, which includes repeat samples taken over a period of three months, is related to a thin (10 or 20 feet in thickness) prominent limestone ridge. Similarly, the anomaly in the Thaynes in drainage DC is related to a thin limestone ridge. Although no prominent limestone ridge was noted in the Thaynes formation in drainage BA, an anomaly of 89 micro-micro Curies per liter exists at a point of abrupt change in stream gradient. The abrupt change in stream gradient is characteristic of the other two areas and suggests that the limestone is also present at the point of the anomaly in drainage BA. Another limestone ridge occurs near the base of the Thaynes formation in the Pinecrest area, where an anomaly of 100 micro-micro Curies per liter is found.

The upper limestone member of the Park City formation also acts as an aquifer, particularly near its contact with the Woodside shale. Radon anomalies are also associated

with the Shinarump conglomerate or Suicide member of the Ankareh shale, although the magnitude is generally small.

A somewhat perplexing difference in radon distribution exists between drainage FE and GE, which are parallel and only about 1,500 feet apart. Drainage FE contains a higher level of radon concentration than drainage GE. Also a large radon anomaly occurs near the Park City-Woodside contact in drainage FE, yet no anomaly occurs in drainage GE. This marked difference may be due to the differences in the two stream channels. The channel of drainage FE is partly bedrock and partly soil derived from bedrock with considerable vegetation. Whether the vegetation is supported by water from the stream or by spring water is not known, although there is presumably some influx of ground water into the stream to maintain the relatively high radon content.

Channel GE is "choked" with cobbles and boulders of Weber quartzite and Almy conglomerate with a thickness of at least 15 feet near the Park City-Woodside contact. Increased turbulance probably contributes to the low radon concentrations. It is also possible that any ground water which enters the channel does so at depth, and then emerges to mix with the stream water in the area of the Woodside shale, where the cobbles and boulders are thinner or absent.

Mill Creek area

An investigation of radon distribution in stream waters

was undertaken in a part of Mill Creek.

The lithology is similiar to that of the Red Butte Canyon and Pinecrest area. The lower half of the Thaynes formation includes three rather thick limestone ridge-forming strata.

Plate 6 shows the distribution of radon in a part of the Mill Creek area. (Also see index map, Figure 3). The geology of the area is adapted after Granger and Sharp (1952).

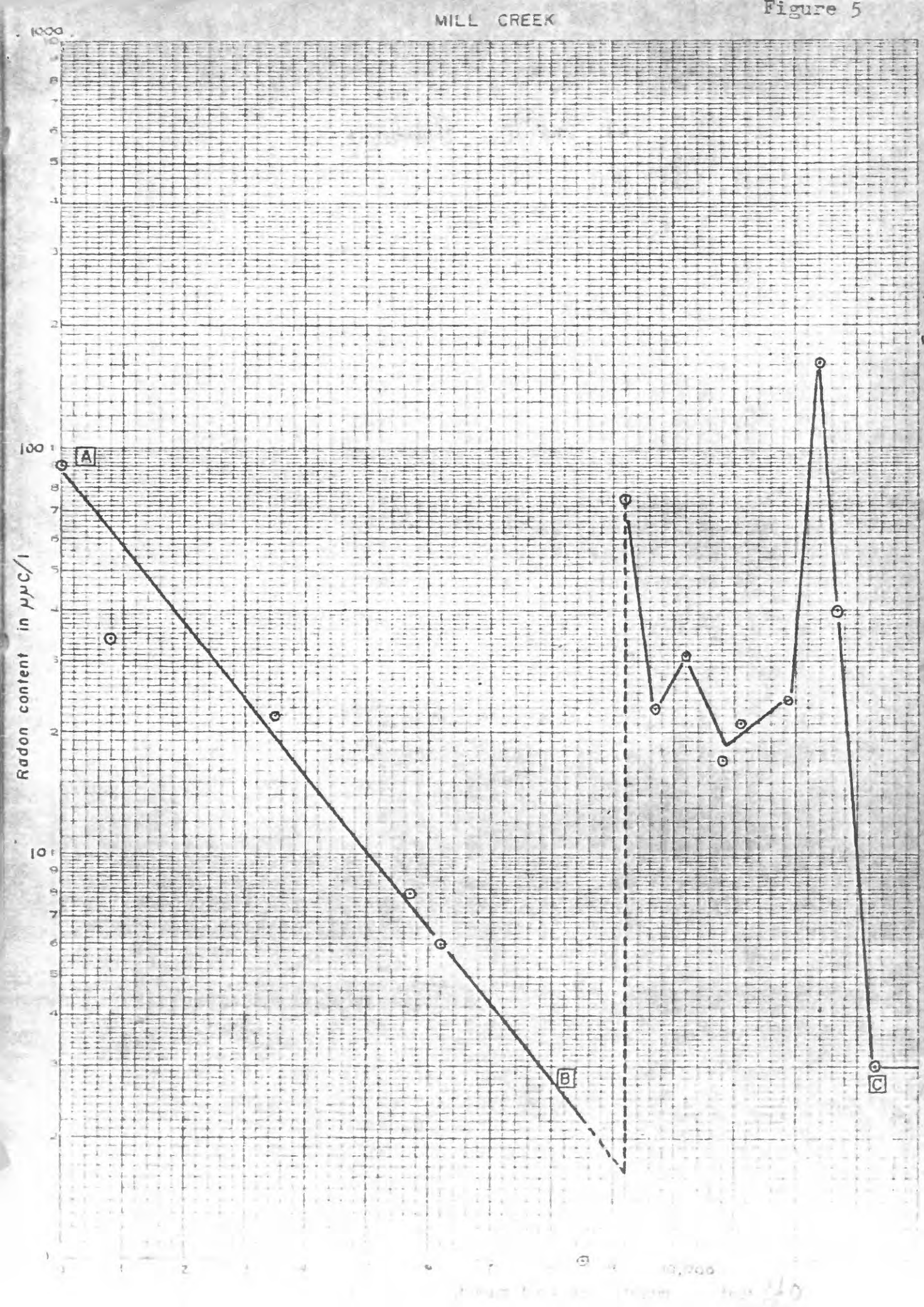
The average gradient between A and C is about 300 feet per mile. About 3 miles downstream from point C, the stream flow was approximately 12 cubic feet per second. Because of water diversion, the stream flow between A and B, perhaps 8 or 10 cubic feet per second, is probably two times as great as the flow between B and C.

Large increases in radon contents were found in stream waters near limestones in the Thaynes and Park City formations. These limestones apparently act as aquifers in a manner similiar to that found in the Red Butte Canyon and Pinecrest area.

The spring at Point A acts as a source for the increase in radon content in the stream water. The radon content in the stream decreases at a slower rate between A and B compared to the usual rate in the Red Butte Canyon and Pinecrest area.

A plot of radon content versus distance of stream flow between A and C is shown in Figure 5. This plot shows that the rate of radon loss occurs as an exponential function. The slope of this curve between A and B is much flatter than those of drainages in the Red Butte Canyon and Pinecrest

Figure 5



area (note the difference in the distance scale), which is probably due to the greater stream volume and lower gradient in the Mill Creek area. The exponential function has a flatter slope between A and B than near point C. This feature is probably due to the smaller stream volume near point C. The slope of the function near point C is almost identical to those in the Red Butte Canyon and Pinecrest area.

As Mill Creek is a fairly wide stream, a series of samples were taken at point A at various positions in the stream to determine whether sampling position is a critical factor. The stream at point A is about 7 feet wide. The radon content, on the basis of this one experiment, varies only about 5 percent with respect to stream position. The results shown in Figure 6 indicate that the radon content is a maximum in the center of stream, and is apparently constant with depth.

City Creek area

A radon survey was also made in a small part of City Creek. (see Plate 7). The geology of the area consists of a sequence of vertically dipping Paleozoic sediments which represent an entirely different section than the Red Butte Canyon area and the Mill Creek area. The Paleozoic strata are unconformably overlain by Tertiary conglomerates and volcanics.

The average stream gradient between D and B is about 800 feet per mile. At point A the stream flow is probably

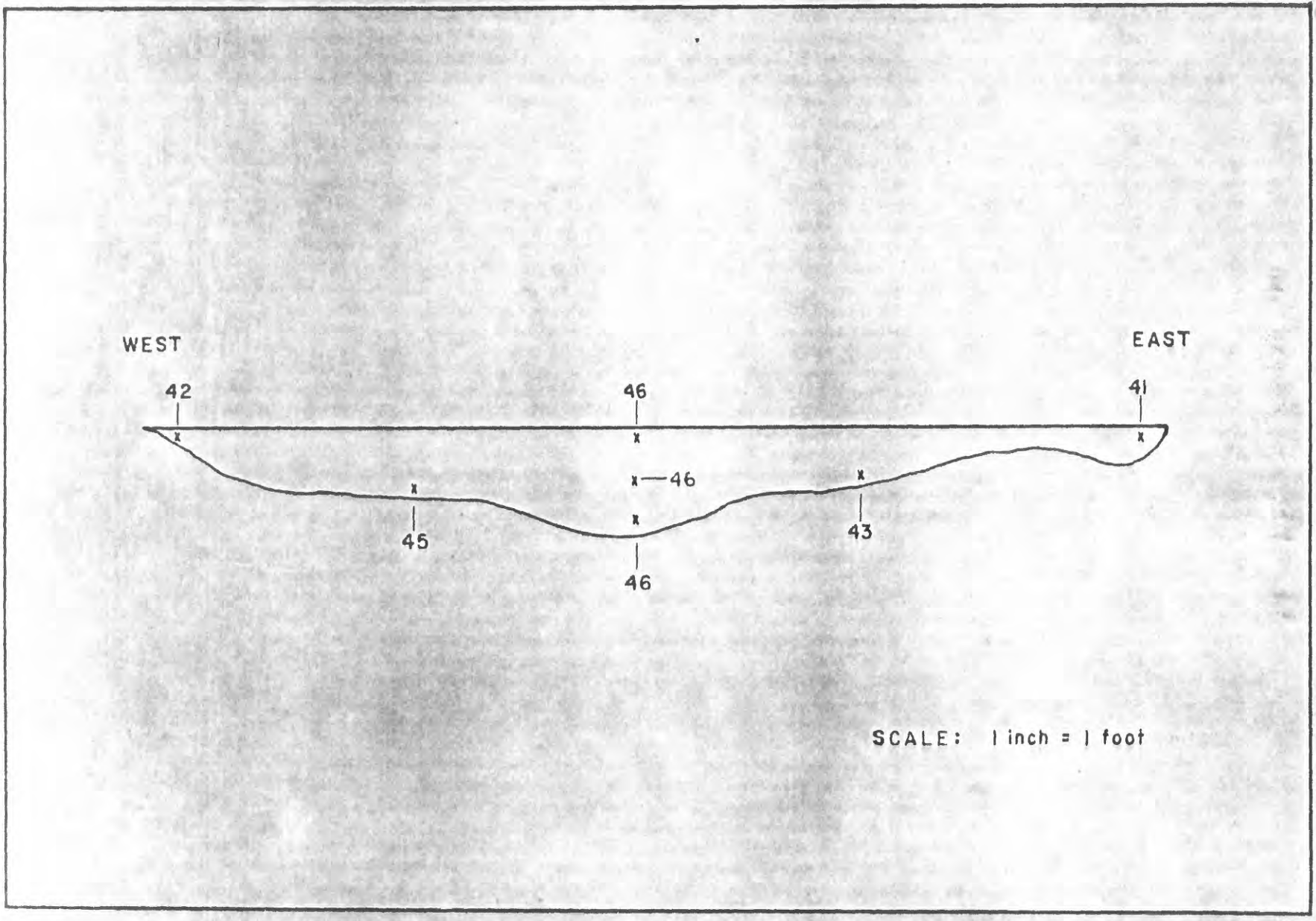


Figure 6 - Cross section of Mill Creek at point A showing radon distribution.

about two cubic feet per second in each fork as based on 1950 measurements.

The results of the radon survey in the City Creek area are similiar to those of the two previous areas. Numerous small springs occurring along the fork CB maintain a higher level of radon concentrations than in fork DB.

Radium in streams and springs

Several radium determinations of stream- and spring-water samples show that the radon is almost completely out of equilibrium with its parent radium. The radium content in each sample is of the order of 2 or 3 micro-micro Curies per liter. Since this small amount approaches the limit of the sensitivity of the instrument, the radium contents may be less. No uranium analyses of the samples were made.

Radiometric surveys

Traverses with a scintillation counter failed to disclose any abnormal radioactivity, except for the phosphatic shale member of the Park City formation. One picked sample of the phosphatic shale contains 0.003 percent equivalent uranium (J. Mytton, U.S. Geological Survey, Denver, Colorado).

Conclusions

Large radon increases in stream waters is a reflection

of relatively large amounts of ground water entering the stream at the point of the anomaly. The radon, which has been introduced into the stream, is gradually flushed to the atmosphere at a rate dependent upon the distribution ratio of radon, the gradient and volume of stream flow, and the nature of the stream channel. The rate of radon loss occurs exponentially with respect to distance of stream travel.

The ability to find aquifers by radon surveys of streams is potentially important in ground-water studies.

Radon surveys of streams may be useful in uranium exploration. The radon contents would necessarily have to be much greater than the magnitude of radon found in this investigation.

Radon was measured in 12 springs in the three areas previously described. Generally, the springs contain more radon than the stream waters. No correlation is apparent between the radon contents and the formations from which they issue. It is possible that such factors as porosity, permeability, rate of flow of ground water, and the emanating power of the radium in the various rocks, may completely overshadow any effects produced by small changes in the radium content of different rock types.

WEBER RIVER PROBLEM

Areal description

Radon determinations in stream waters and related springs were applied to a definite ground-water problem in a part of the Weber River drainage area, near Ogden, Utah (see Plate 8).

The Weber River in this area flows due west through a steep-walled canyon in the northern Farmington Mountains. The Farmington Mountains, a division of the Wasatch Range, are characterized by a well-exposed middle (?) pre-Cambrian metamorphic terrane.

The investigation was done in February, 1954, when the Weber River was at a low stage of flow.

General geology

The geology of the Farmington Mountains, including the Weber Canyon, was investigated by Bell (1951, 1952), and the following summary of the geology of the Weber Canyon area and the geology presented on the map showing radon distribution (see Plate 8) is based on Bell's work.

The pre-Cambrian rocks were classified and mapped according to the concept of "mineral facies", as defined by Eskola. Three facies occur in the Weber Canyon area. Two facies represent progressive metamorphism: migmatite, which is essentially a banded hornblende-biotite gneiss, and granulite which is the moderately coarse-grained

product of high-grade regional metamorphism. The granulite has a lens-like fabric with alternating layers of light and dark minerals, and for the most part looks like an intrusive granite. Relict anticlines and synclines are clearly evident in the field, and may be traced through various metamorphic facies.

The third, or greenschist, facies is presumably developed along Laramide thrust plates and represents a diaphthorite zone of retrograde metamorphism. The retrograde greenschist is predominately a chlorite phyllonite. Ten thrust plates are exposed near Weber Canyon at vertical intervals of 500 to 1,000 feet, with a thickness of from 2 to 50 feet. A general westerly dip of 10° to 30° is characteristic of the thrust plates.

The east side of the area is unconformably overlain by the Knight (?) formation of Eocene age.

A cross section of the area, adapted from Bell (1951), is shown on Plate 8.

Statement of the problem

It has been previously established in this paper that the addition of ground water to a stream is reflected by an increase in the radon content of the stream water. This principle was then applied to a definite ground-water problem, which was investigated in cooperation with John H. Feth and Herbert A. Waite both of the Ground Water Branch, U.S. Geological Survey.

Through careful measurements by Feth, it was established that the Weber River increased in flow from 2.82 cubic feet per second, at point A, to 7.50 cubic feet per second, at point D, in about one and one-half miles (Plate 8). The only areas of visible addition to the stream flow, at points E, F and G, amounted to about 20 gallons per minute.

The problem was to determine whether the stream volume increased due to a continual influx of ground water along the stream course between A and D or whether the bulk of the increase was confined to the limited area of visible seeps, at points E, F and G. It was impossible to gauge the stream flow between A and D because of the abundance of large boulders in the stream channel. There was also a question of whether the increase in stream volume was due to the influx of bedrock or bank storage ground water.

Results and conclusions

The radon contents of stream waters and springs (marked with asterisks) are shown on a geologic map of the Weber Canyon area (Plate 8).

Radon contents of the major springs in the Gateway Tunnel, U.S. Bureau of Reclamation Project, were determined. The radon determinations in the tunnel, which are underlined on the map, were collected from galvanized troughs or drips from the back, and are considered to be low by at least 50 percent, and possibly by a factor of two or three or more.

A scintillation counter traverse through the tunnel failed to show any abnormal radioactivity except in a small area 1,000 feet from the east portal. A sample was collected by John Powers, U.S. Geological Survey, Salt Lake City, Utah, who made the scintillation counter traverse. The sample, which was taken from a pod-like mass of pegmatitic material, contained 0.003 percent equivalent uranium.

Quality-water measurements were made on three spring and four stream samples, at points A through G, by J.G. Connor, Quality of Water Branch, U.S. Geological Survey, Salt Lake City, Utah. These measurements were made partly to aid in ground- and surface-water studies in the Ogden, Utah area, and partly to determine if any relationships can be established between quality-water and radon measurements. The radon samples and quality-water samples were taken at the same time. The results of the quality tests are listed in table 1.

The distribution of radon in the Weber River shows a definite relation to the springs at E, F, and G, and forms a pattern similiar to that found in the streams in the Wasatch Mountains near Salt Lake City, Utah. Figure 7 shows the plot of radon loss versus distance of stream flow. The loss of radon occurs exponentially.

In addition to the areas of visible springs, ground water contributes a small amount to the stream flow below the railroad bridge in the S-shaped part of the stream and a larger amount in a zone between D and K. The large addition of ground water in the zone between D and K is

Table 1.--Quality of water data, Weber River, Feb. 15, 1954*

Sample Location	Temp. °F	pH	HCO_3 ppm	SO_4 ppm	Cl ppm	Total hardness as $CaCO_3$-ppm	Non-carbonate hardness-ppm	Specific conductance micro-mhos
Stream Samples								
A	39	8.1	280	32	26	257	27	554
B	35	8.3	277	32	26	256	29	549
C	42	8.0	256	32	22	234	24	512
D	42	8.2	218	28	20	200	21	446
Spring Samples								
E	47	7.6	243	32	19	220	21	482
F	46	7.8	248	32	18	222	19	487
G	45	7.7	228	28	19	210	23	465

*Data from J.G. Connor, Quality of Water Branch, U.S. Geological Survey, Salt Lake City, Utah

supported further by the quality water measurements (see Table 1). The total hardness and specific conductance measurements show that the solids content of the stream at point D is less than the solids content upstream at points A, B, and C, and also less than the solids content of the springs at E, F, and G. Assuming that the stream is not precipitating part of its solid content, an addition of better-quality water must therefore occur between G and D.

The area of visible springs at E, F and G, as well as at D and K, which are the other areas of large ground-water influx, show a marked relation to the thrust plates in the canyon. The intersection of the projection of the Gateway Tunnel in cross section A-A' with the thrust plates also seems to indicate that the thrusts control the ground-water movement in the area. If bank storage is the controlling factor in the movement of ground water in this area, the entrance of ground-water into the stream, and hence the radon anomalies in the stream, would probably occur in the areas where a large amount of alluvial material is present.

An attempt was made to use the radon measurements of stream- and spring-waters to calculate the increments of stream volume increase between points A and D, where intermediary stream gauging was impossible, because of the abundance of large boulders in the channel. The results of the calculations, which are believed to be

reasonable estimates, are shown on Plate 8 at points F, G, the zone between D and K, and the small radon anomaly in the S-shaped part of the stream. At point F, for instance, the amount of influx of ground water, containing approximately 500 micro-micro Curies per liter, was determined to be 1.2 cubic feet per second, in order to raise the radon concentration in the stream from 5 (at point B) to 156 (at point C) micro-micro Curies per liter. The calculations account for about 60 percent of the stream flow increase between A and D.

The following assumptions were made in the calculations:

1. The stream does not lose or gain in volume between the points of radon anomalies; that is, the volume at B is 2.82 + .04 cubic feet per second. Similarly, the stream flow at point K is assumed to be 2.82 + .04 + 1.2 + .75 cubic feet per second.

2. Radon contents of the springs are representative of all ground water entering the stream at the particular point.

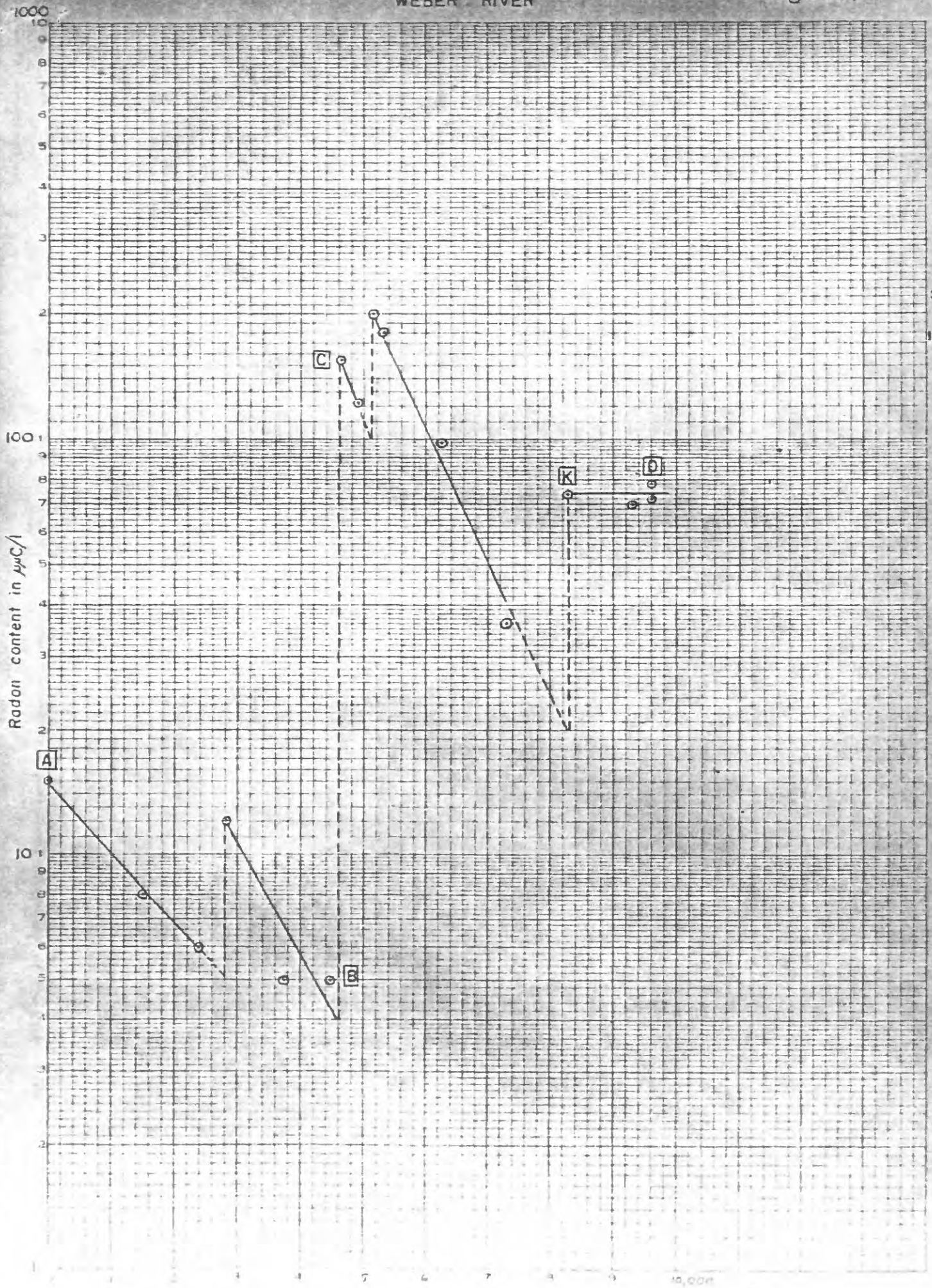
3. Complete mixing of radon occurs in the stream waters.

4. The rate of radon loss in the stream is constant. For instance, at a point just upstream from K, the stream is assumed to contain about 20 micro-micro Curies per liter, based on the exponential rate of radon dissipation between G and K (see Figure 7).

5. In the area DK, the radon content of the ground water entering the stream is assumed to be 600 micro-micro

WEBER RIVER

Figure 7



Curies per liter, based on the average radon content of known springs at E, F, and G.

In conclusion, the bulk of the ground water which enters and increases the flow of the Weber River can be considered bed rock rather than bank storage ground water. The movement of ground water in the area is apparently controlled by the diaphthorite thrust plates.

SUMMARY AND POTENTIAL USES OF RADON DETERMINATIONS IN GEOLOGIC PROBLEMS

Ground-water problems

Areas of relatively large amounts of ground-water influx into small turbulent streams can be determined by radon measurements. An area of ground-water influx is marked by an abrupt increase in the radon content of the stream. The high radon content gradually decreases down stream at a rate dependent upon the radon distribution ratio, the rate of stream flow, the gradient of the stream, and the nature of the stream channel. The loss of radon from the streams occurs as exponential functions of various slopes with respect to distance of stream flow. The source of the radon can be detected rather accurately, provided short intervals of sample spacing are used.

In the areas studied in the Wasatch Mountains, the high radon anomalies can generally be related to definite stratigraphic horizons.

The technique of locating aquifers by radon measurements in stream waters was applied to a definite ground-water problem in a part of the Weber River area. The increase in stream flow was found to occur primarily at three rather definite areas, where ground water is entering the stream, apparently along thrust faults.

Calculations, which are believed to be reasonable estimates, were made to determine the amount of ground

water entering the Weber River. The calculations are based on radon concentrations in stream waters and adjoining springs.

The results of the present investigation on the distribution of radon in streams and related springs should have potential applications in the field of ground water.

Uranium exploration

Among all the daughter products of uranium, radon, an inert gas, is the most susceptible to migration. Thus, radon is a potentially important tracer in uranium exploration.

Although the present investigation of radon in natural waters was carried on in areas in which no known uranium ore bodies occur, similiar radon studies could be extended to areas that do contain uranium ore bodies.

Proposed future work

Radon surveys of natural waters should be extended into areas containing uranium ore bodies in order to determine the feasibility of such surveys as an additional tool in uranium exploration.

Further investigations of possible applications of radon determinations to ground water studies is contemplated in cooperation with the Ground Water Branch, U.S. Geological Survey, Salt Lake City, Utah.

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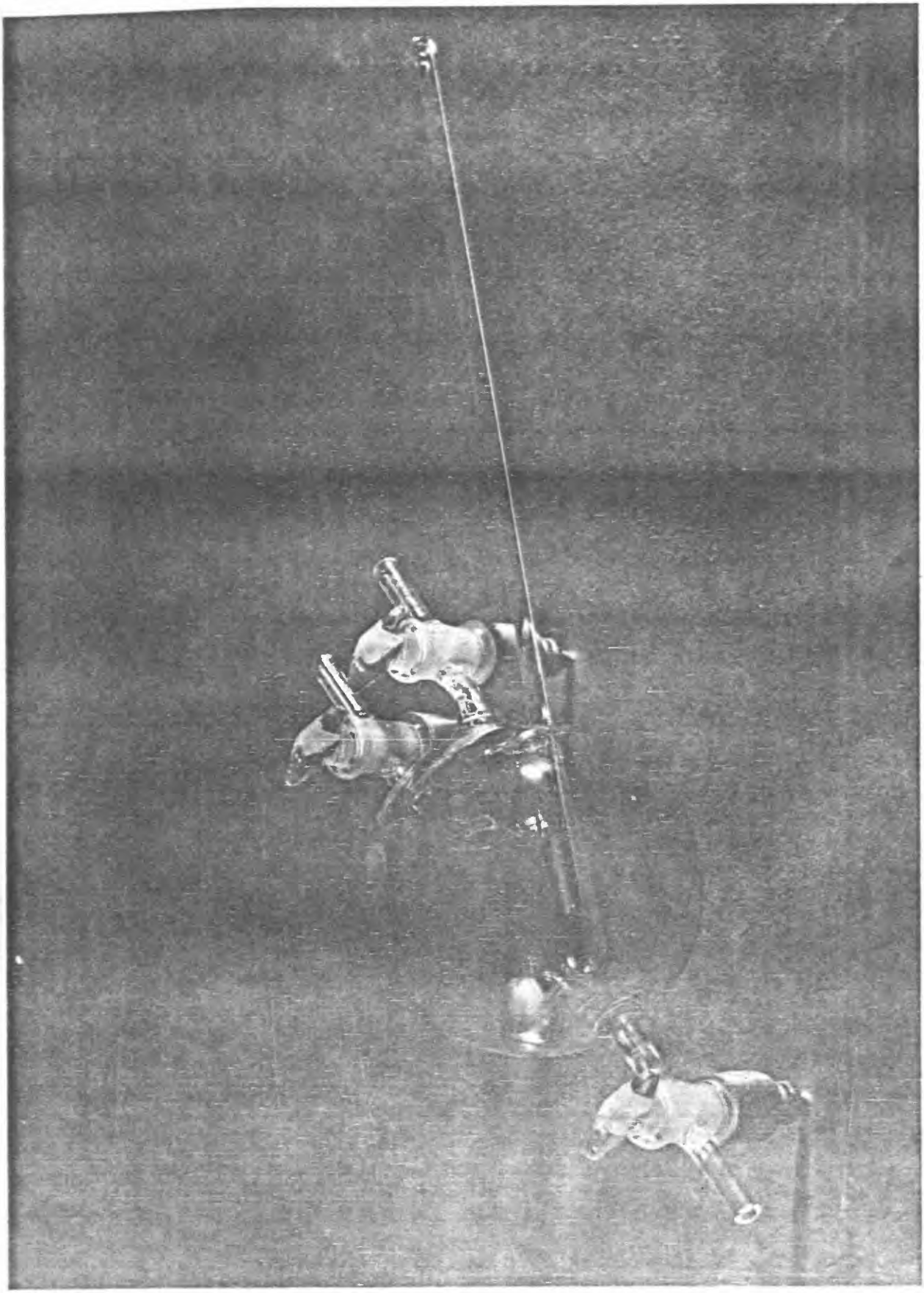


Plate 3 - Radon partition device

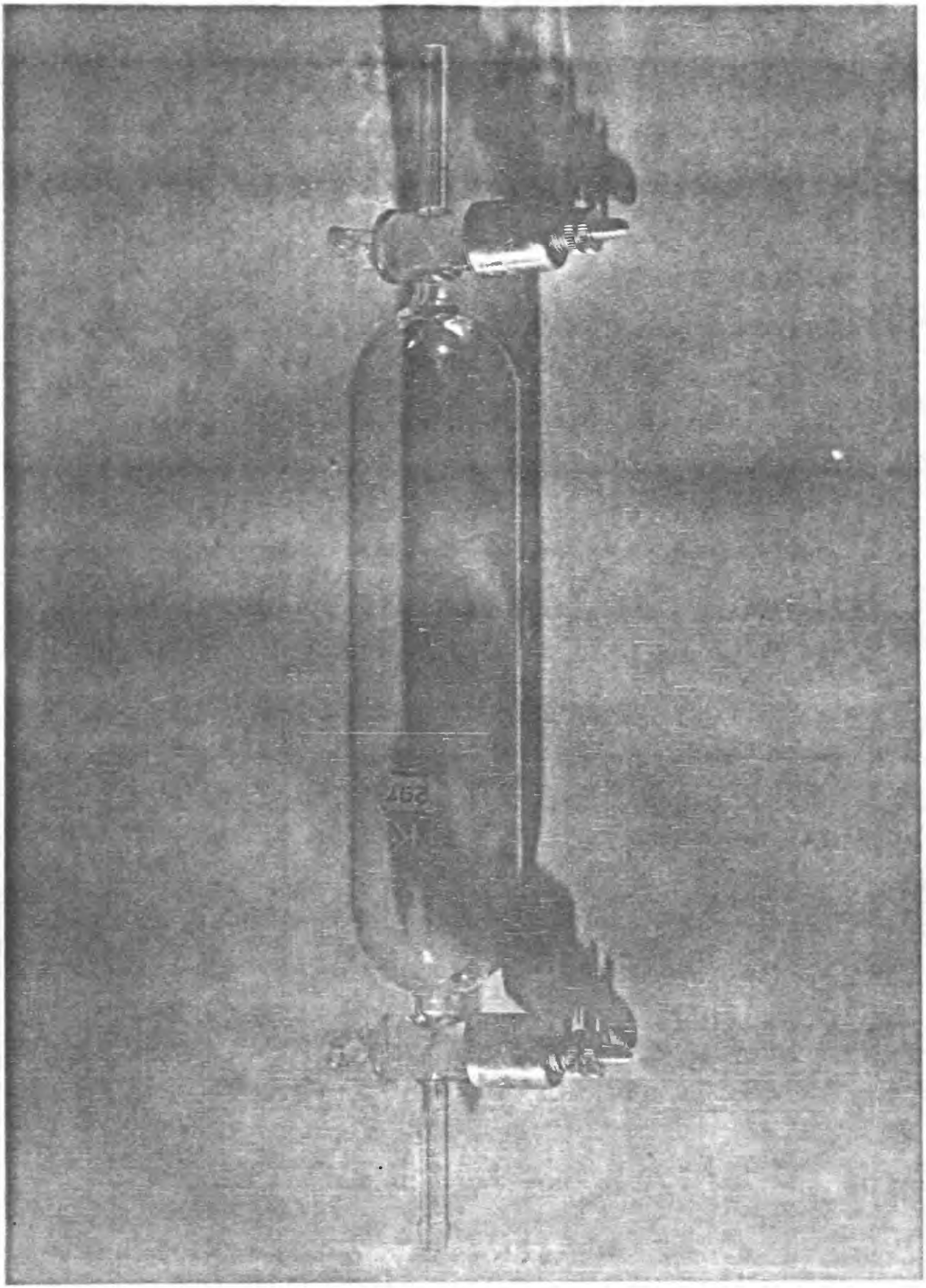


Plate 4 - Gas amplifier tube.

PLATE 5

EXPLANATION

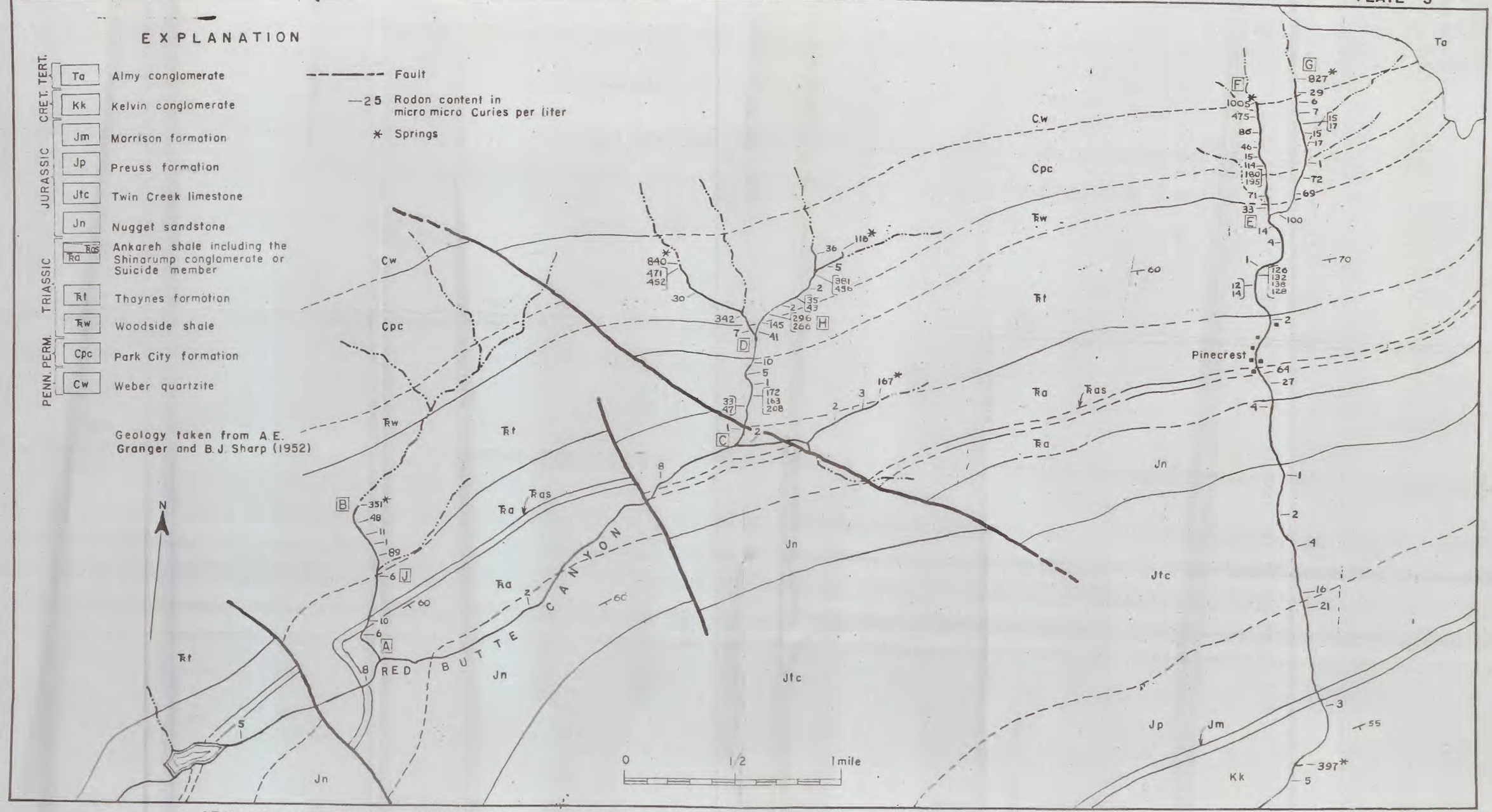
CRET. TERT.	Ta	Almy conglomerate
JURASSIC	Kk	Kelvin conglomerate
	Jm	Morrison formation
	Jp	Preuss formation
	Jtc	Twin Creek limestone
	Jn	Nugget sandstone
TRIASSIC	Ra / Ras	Ankareh shale including the Shinarump conglomerate or Suicide member
	Rt	Thaynes formation
PENN. PERM.	Rw	Woodside shale
	Cpc	Park City formation
	Cw	Weber quartzite

Fault

—25 Rodon content in micro micro Curies per liter

* Springs

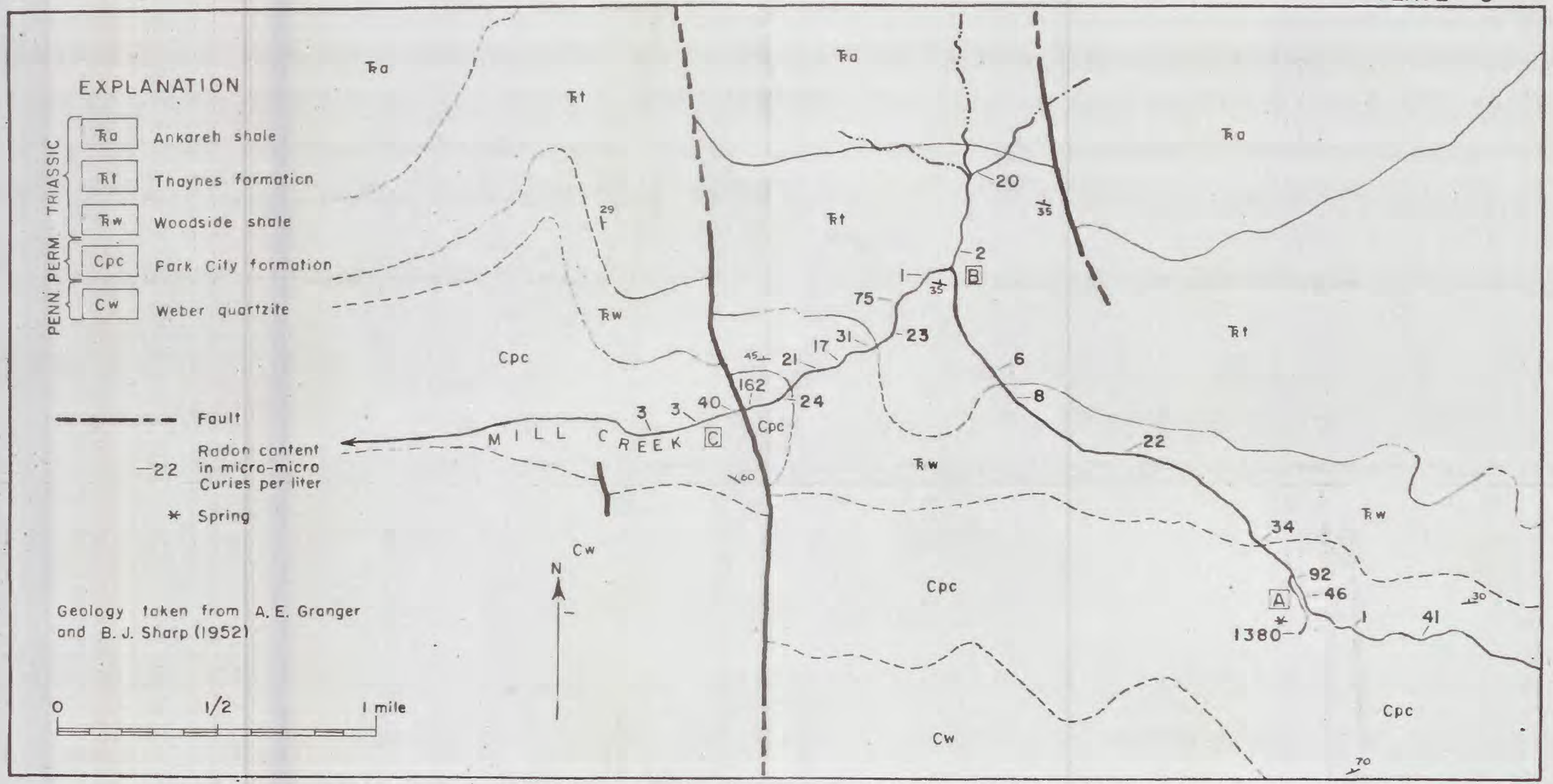
Geology taken from A.E. Granger and B.J. Sharp (1952)



GEOLOGIC MAP OF RED BUTTE CANYON AND PINECREST AREA SHOWING RADON DISTRIBUTION IN STREAMS AND SPRINGS

54-259

PLATE 6



GEOLOGIC MAP OF PART OF MILL CREEK AREA SHOWING RADON DISTRIBUTION IN STREAMS AND SPRINGS

54-259

PLATE 7

EXPLANATION

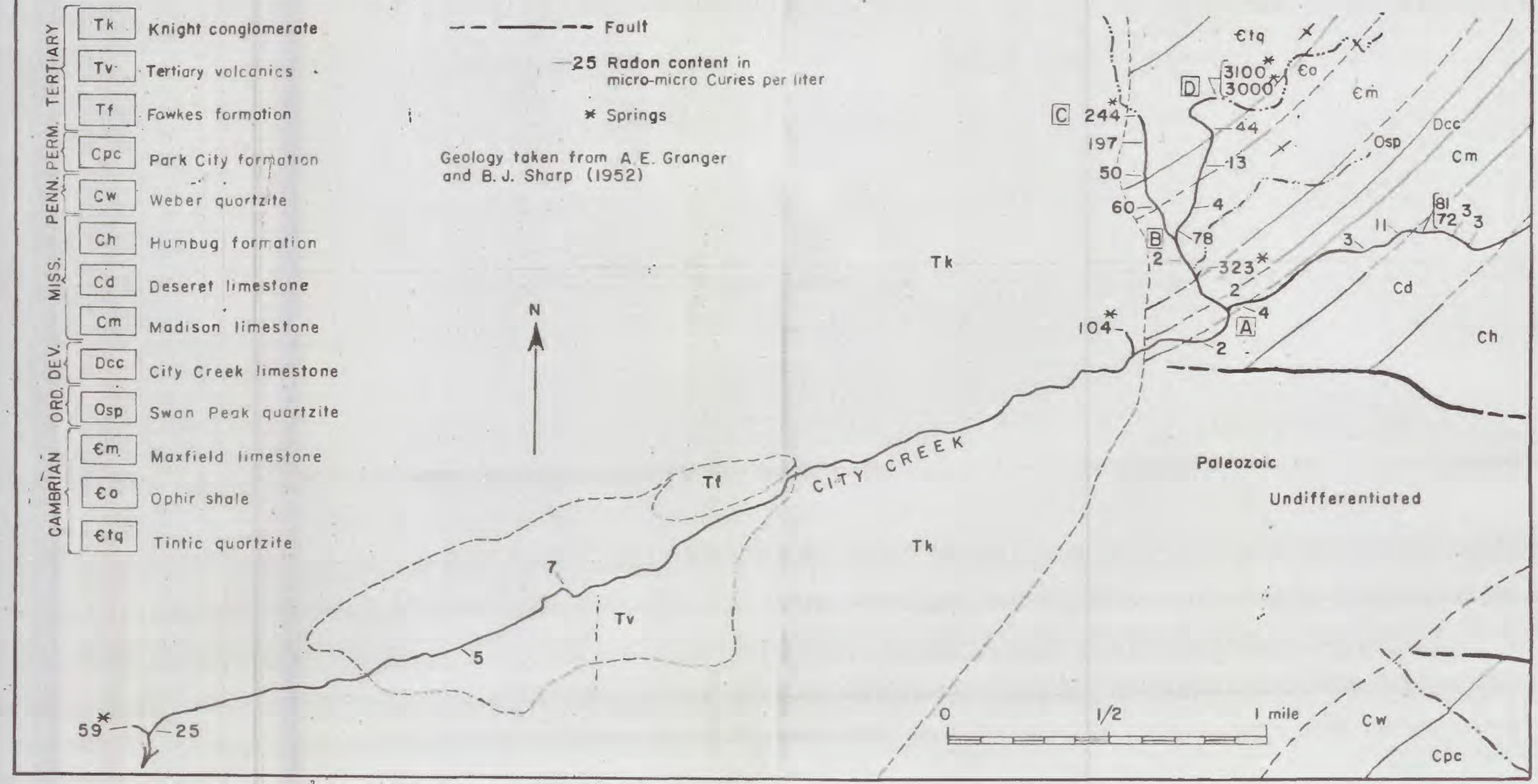
TERTIARY	Tk	Knight conglomerate
	Tv	Tertiary volcanics
	Tf	Fowkes formation
PENN. PERM.	Cpc	Park City formation
	Cw	Weber quartzite
MISS.	Ch	Humbug formation
	Cd	Deseret limestone
	Cm	Madison limestone
ORD. DEV.	Dcc	City Creek limestone
	Osp	Swan Peak quartzite
CAMBRIAN	€m	Maxfield limestone
	€o	Ophir shale
	€tq	Tintic quartzite

Fault

25 Radon content in micro-micro Curies per liter

* Springs

Geology taken from A. E. Granger and B. J. Sharp (1952)



GEOLOGIC MAP OF PART OF CITY CREEK AREA SHOWING RADON DISTRIBUTION IN STREAMS AND SPRINGS

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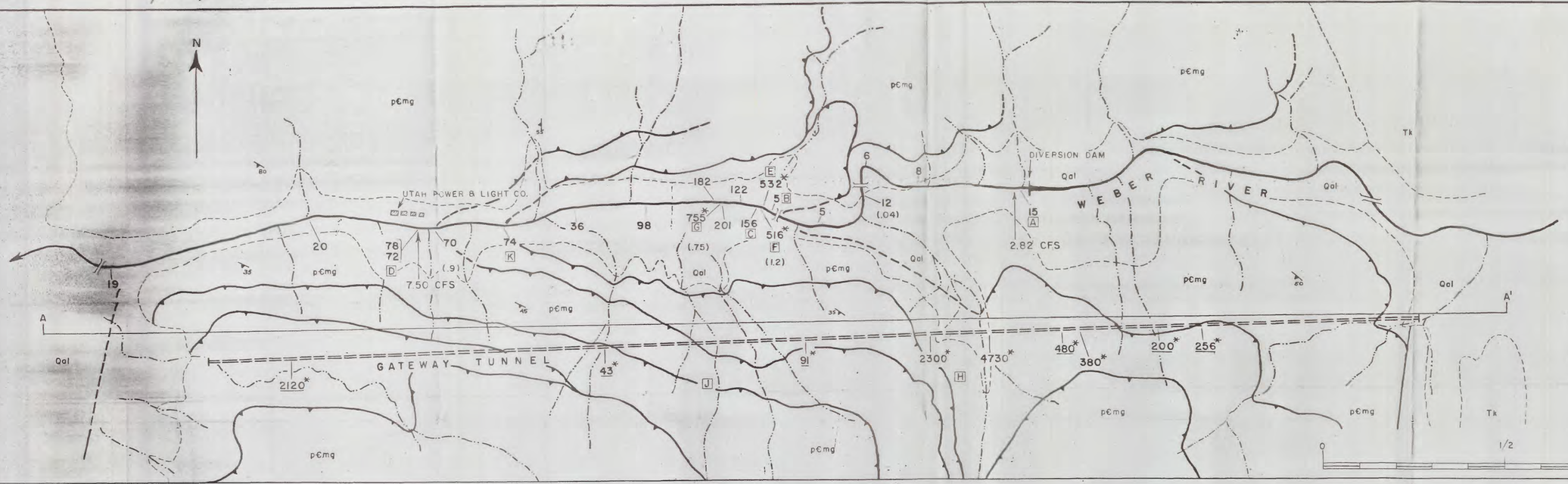
part 1 of 8

part 1 PLATE 8

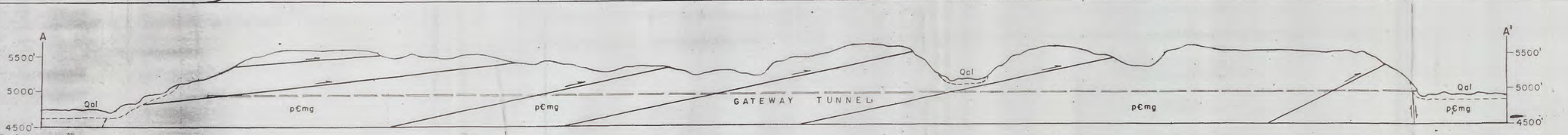


EXPLANATION

- Qal — Alluvium, landslides and lake sediments
- Tk — Knight(?) formation
- p€mg — Migmatite, and granulite facies, undifferentiated

- Normal fault
- Diaphthorite, product of thrust faulting. Barbs on side of upper thrust plate
- 50 — Strike and dip of foliation
- 36 — Radon content in micro-micro Curies per liter
- * — Springs
- (1.2) — Calculated increments of ground-water addition to steam flow, in cubic feet per second. Based on radon measurements
- 7.50 CFS — Stream flow measurements, in cubic feet per second

Underlined radon measurements in Gateway Tunnel springs are minimum values



Base map from U. S. Bureau of Reclamation, Ogden, Utah

Geology adopted from G. L. Bell (1951)

GEOLOGIC MAP AND CROSS SECTION OF PART OF THE LOWER WEBER RIVER AREA SHOWING RADON DISTRIBUTION IN STREAM AND SPRING WATERS

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